Hochdynamische Materialcharakterisierung für Zug-, Druck- und Schubbelastung unter Verwendung der Split-Hopkinson Bar Methode

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Lehrstuhl für Carbon Composites

gestiftet von SGL GROUP THE CARBON COMPANY

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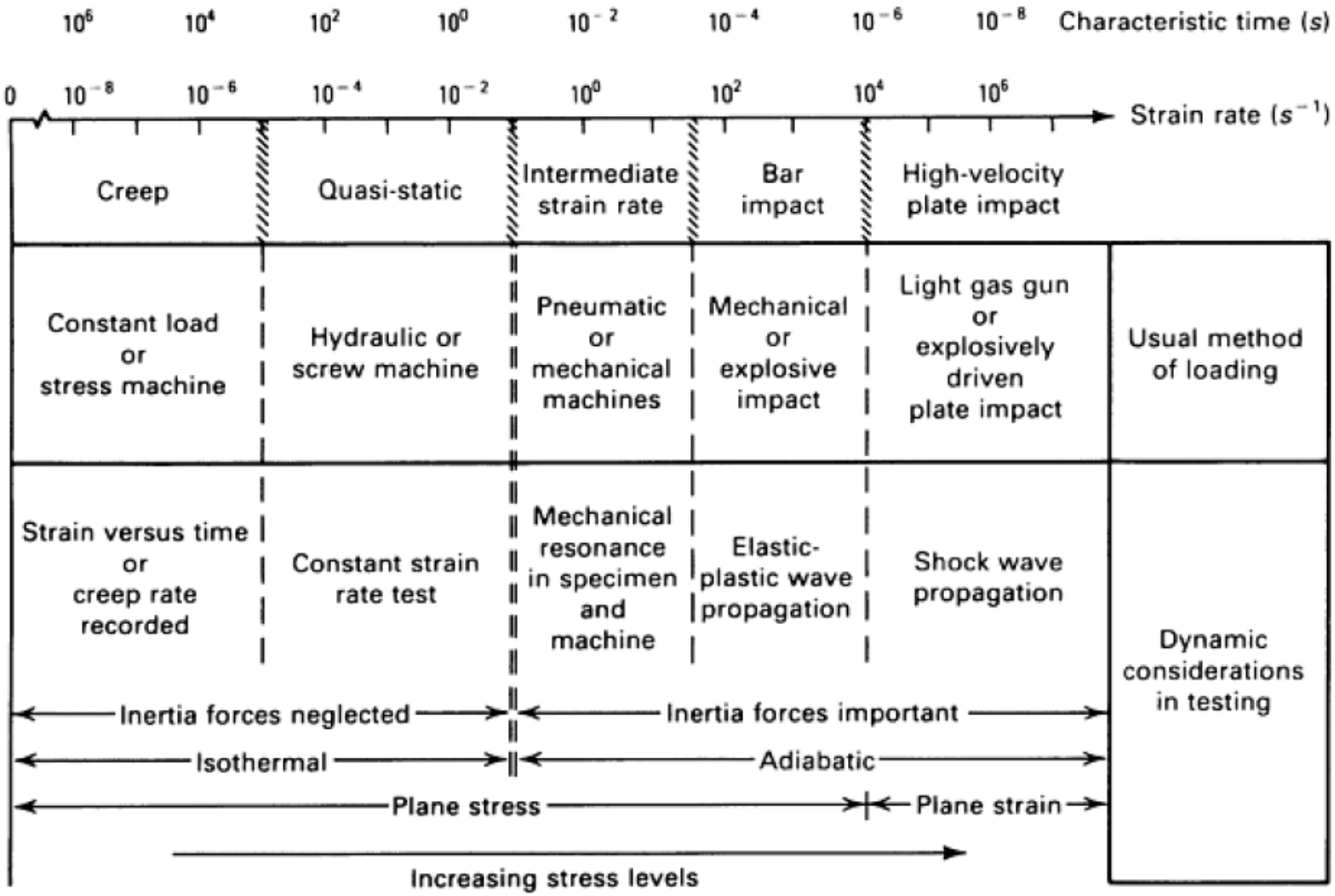
- Test Examples with Compression-Bar Setup
- Test Examples with Tension-Bar Setup

Introduction of Split-Hopkinson Bar Test Method

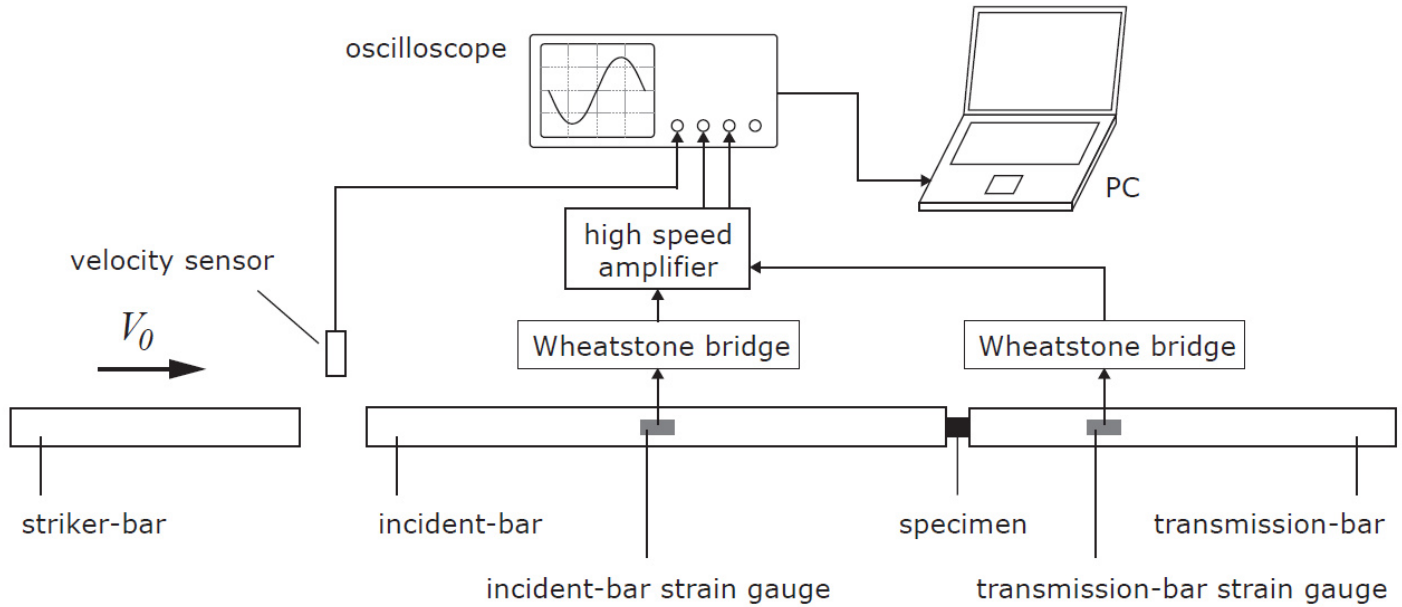
Strain Rate Regimes and Associated Experimental Conditions

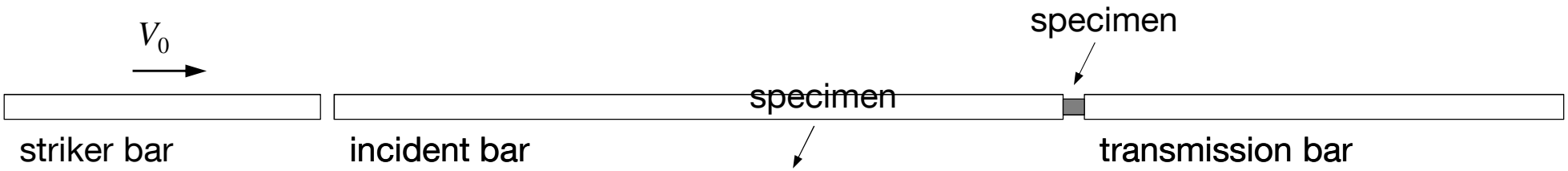


[ASM Handbook Vol 8]

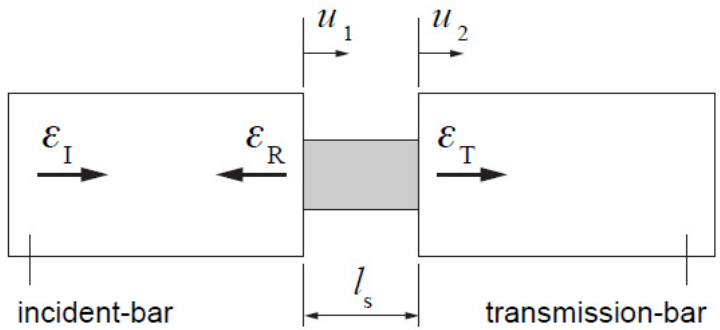
Classic SHPB Setup

$$\dot{\varepsilon} \approx 10^2 - 10^3$$

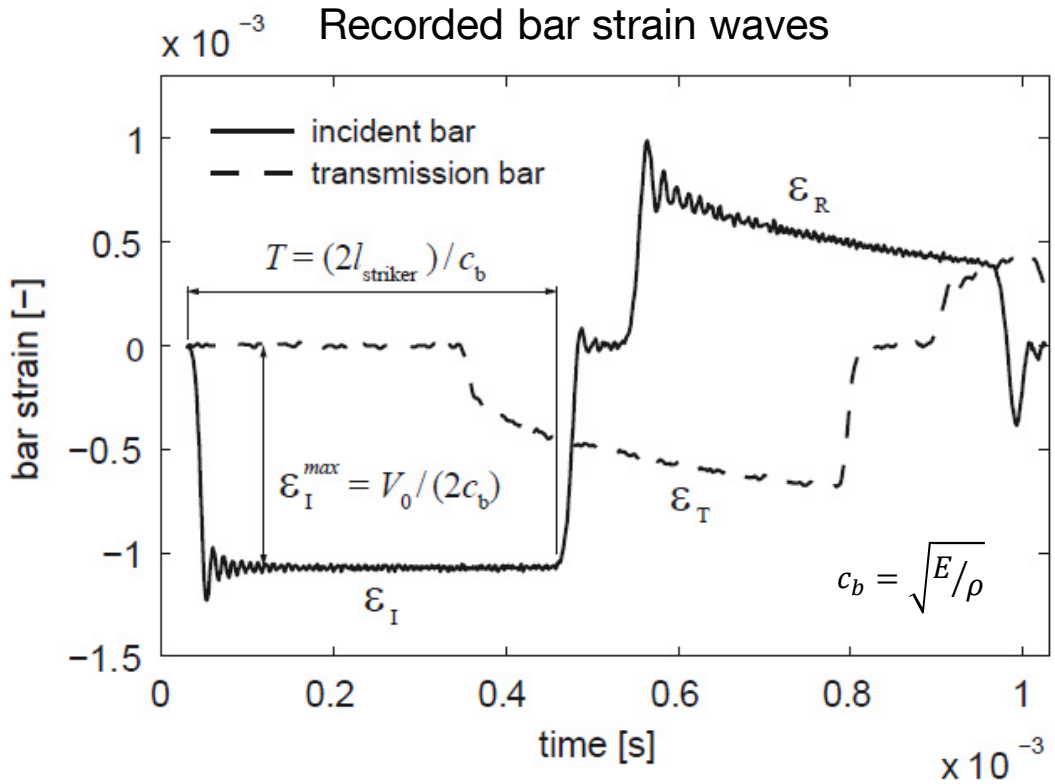




SHPB Analysis

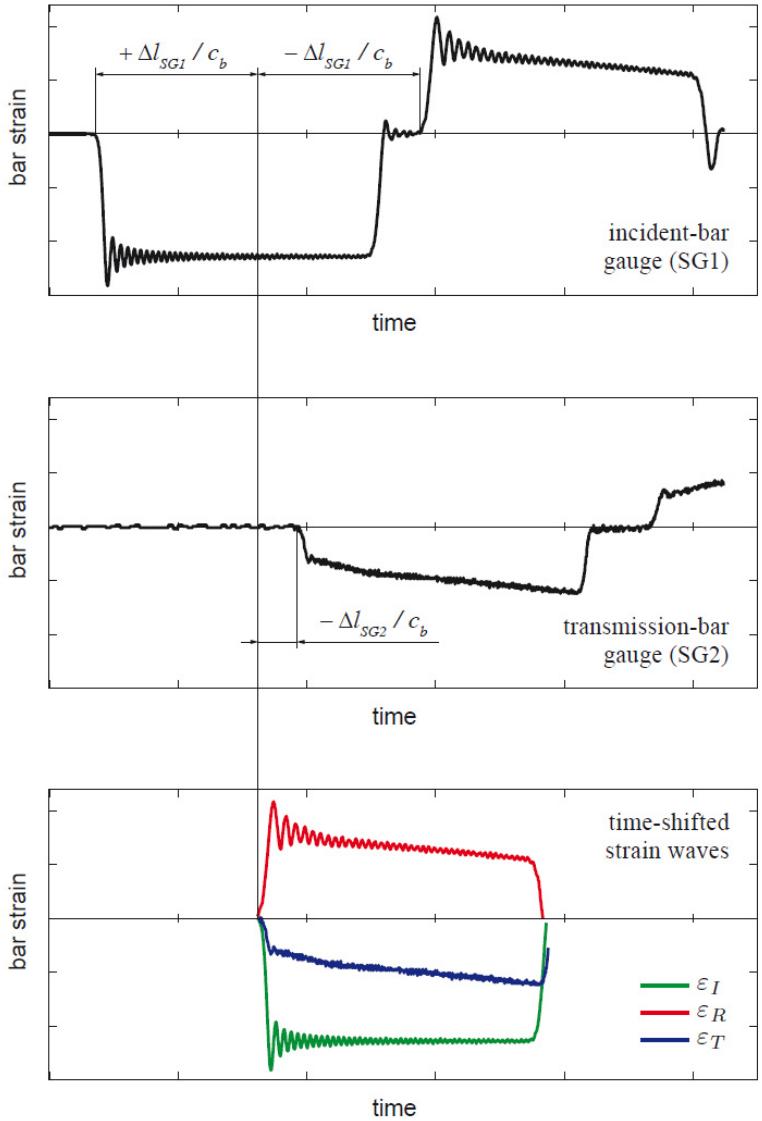


Recorded bar strain waves



Bar strain waves are measured at the bar strain gauges at different times and away from the specimen but are generated at the same time and act simultaneously on the specimen

Time Shift



SHPB Analysis

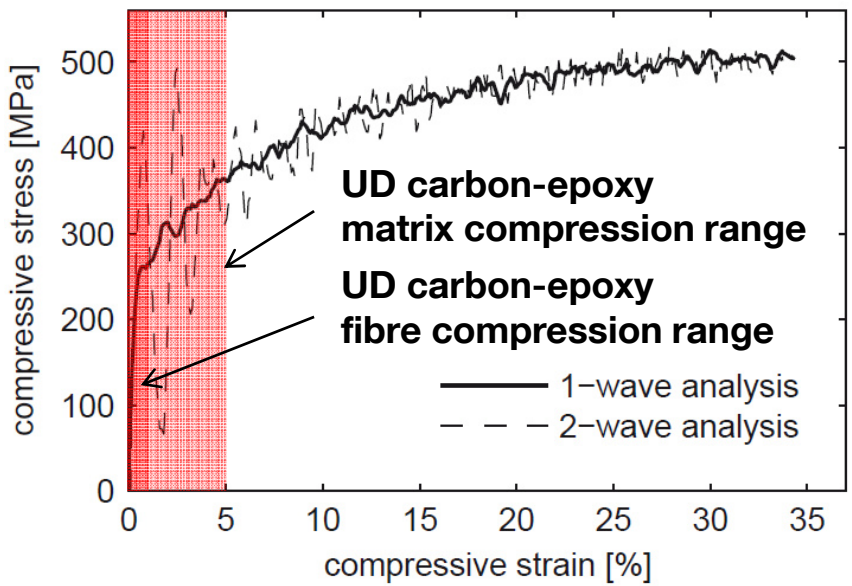
Specimen strain rate $\dot{\varepsilon}_s = \frac{c_b}{l_s}(-\varepsilon_I + \varepsilon_R + \varepsilon_T)$

Specimen strain $\varepsilon_s = \frac{c_b}{l_s}\int(-\varepsilon_I + \varepsilon_R + \varepsilon_T)\,dt$

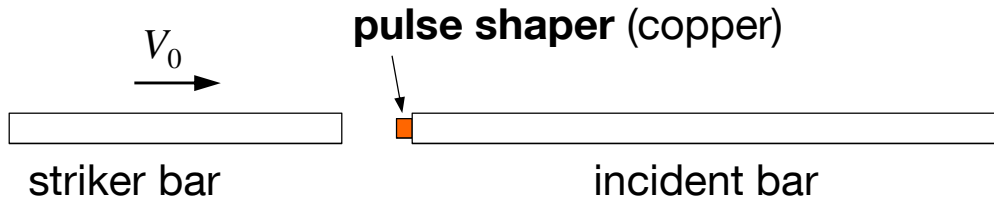
Specimen stress (1-wave) $\sigma_s = \frac{A_b}{A_s}E_b\varepsilon_T$

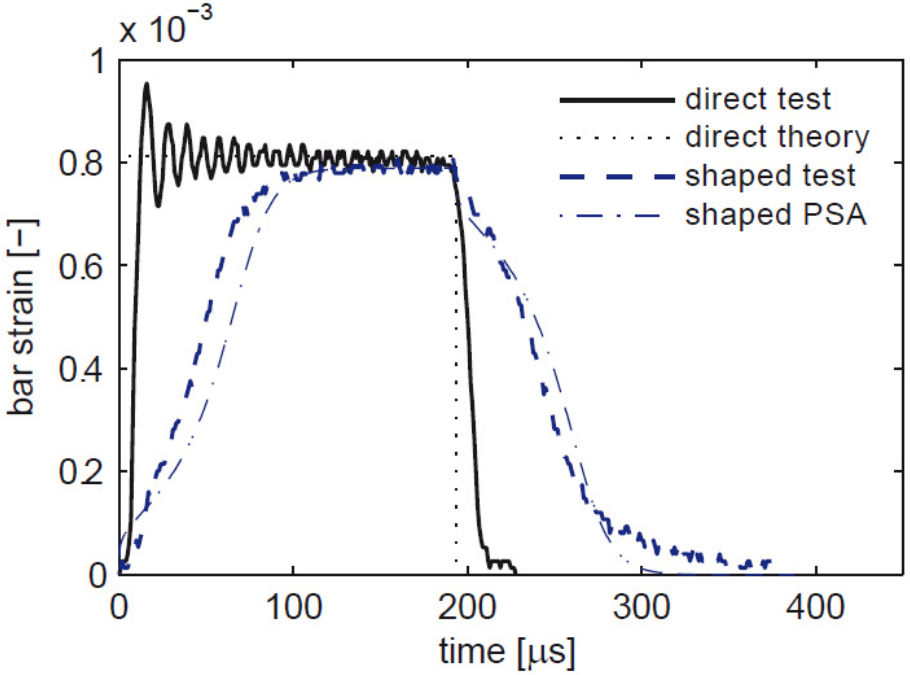
(2-wave) $\sigma_s = \frac{A_b}{A_s}E_b(\varepsilon_I + \varepsilon_R)$

Dynamic stress-strain response

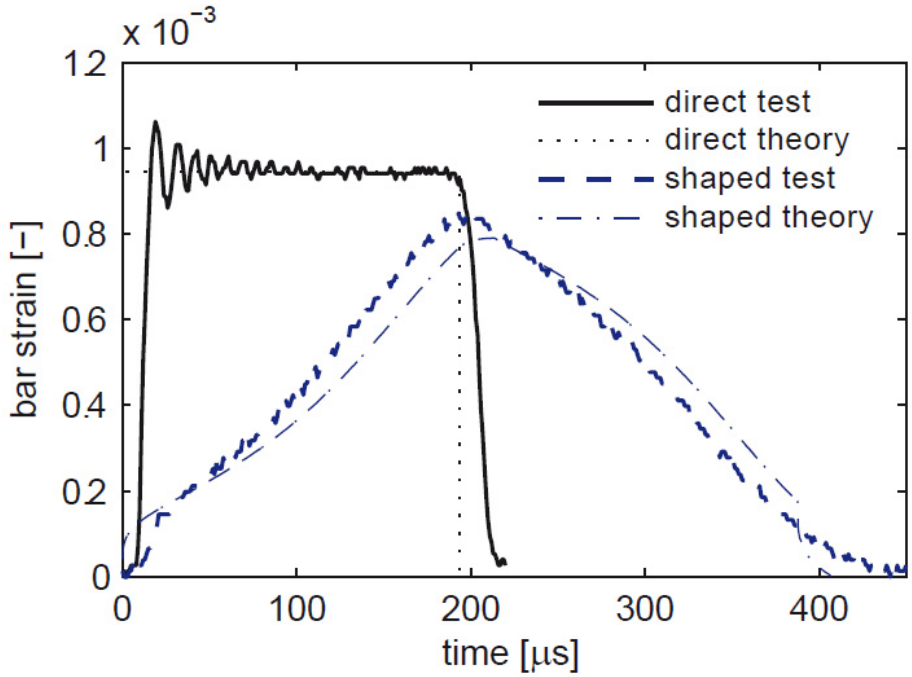


Pulse Shaping





Trapezoidal shaped compressive incident wave



Ramp shaped compressive incident wave

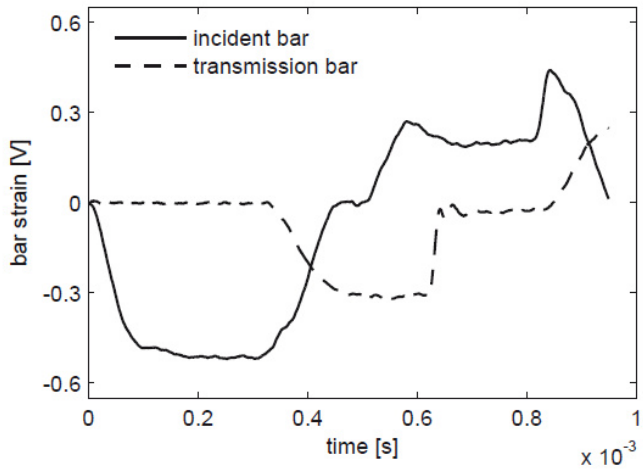
Incident wave shape matches specimen stress-strain response (non-linear vs. linear)

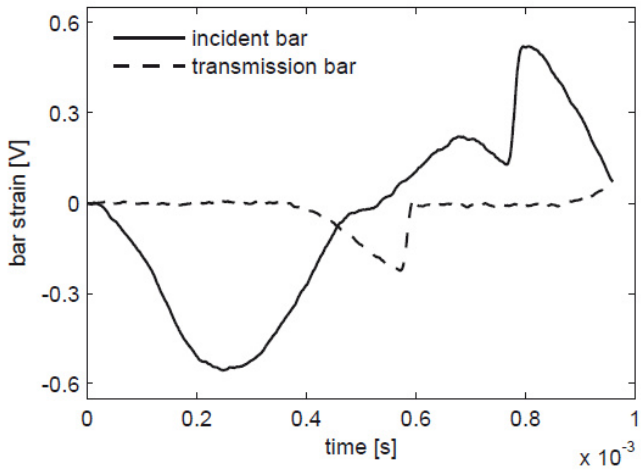
- near constant strain rate
- improved dynamic force equilibrium

trapezoidal / non-linear specimen

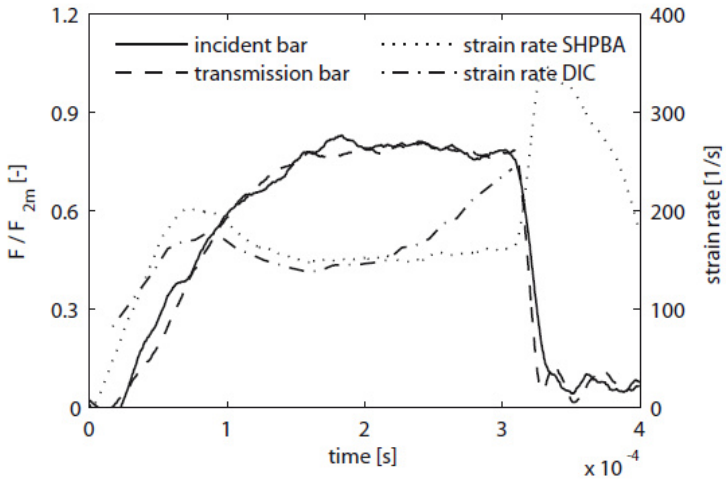
ramp-shaped / linear specimen

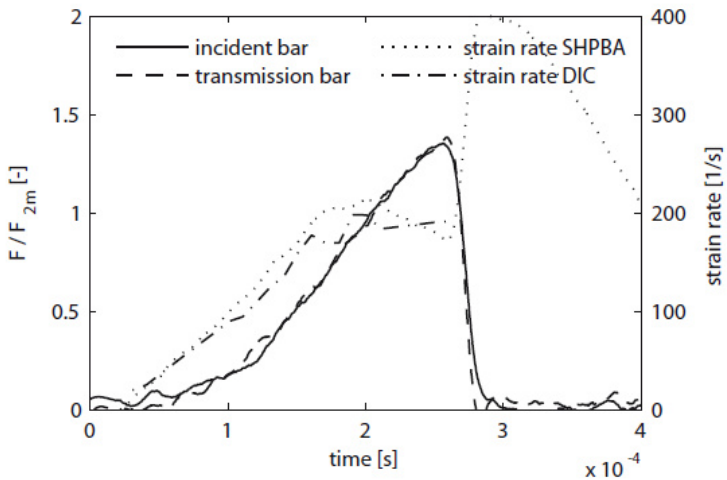
bar strain waves



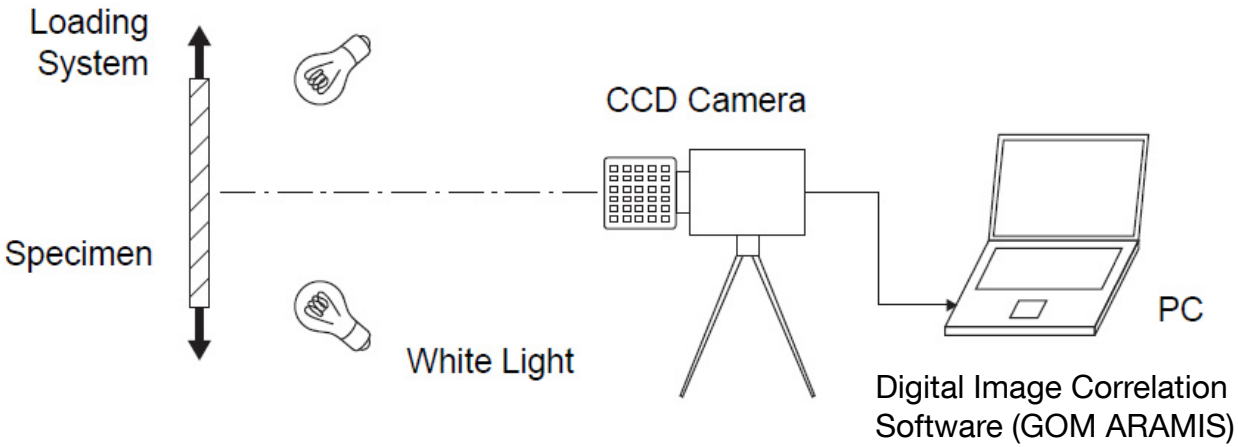


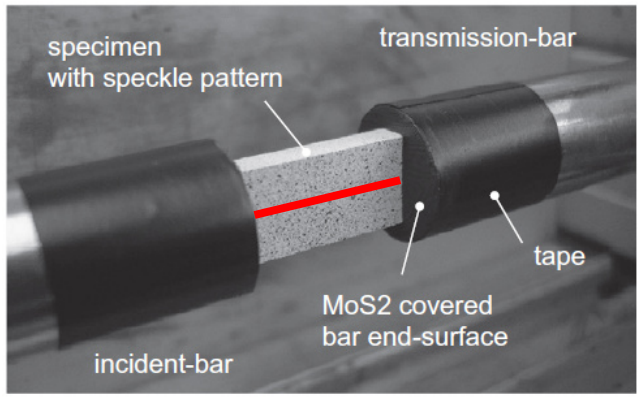
dynamic equilibrium and strain rate (intermediate rate)



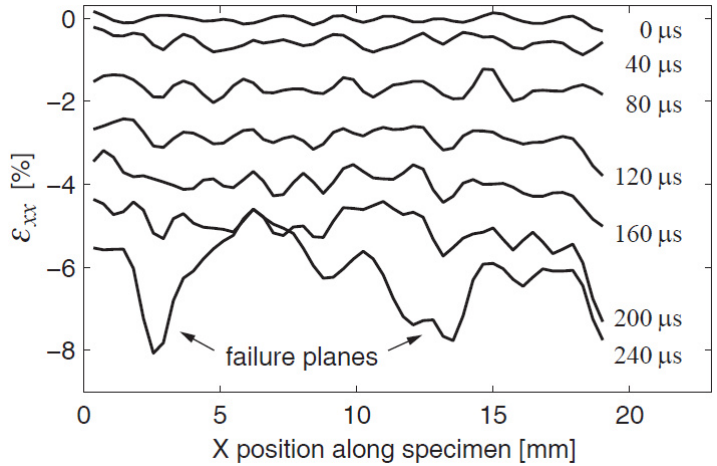


Strain Measurement via Digital Image Correlation (DIC)



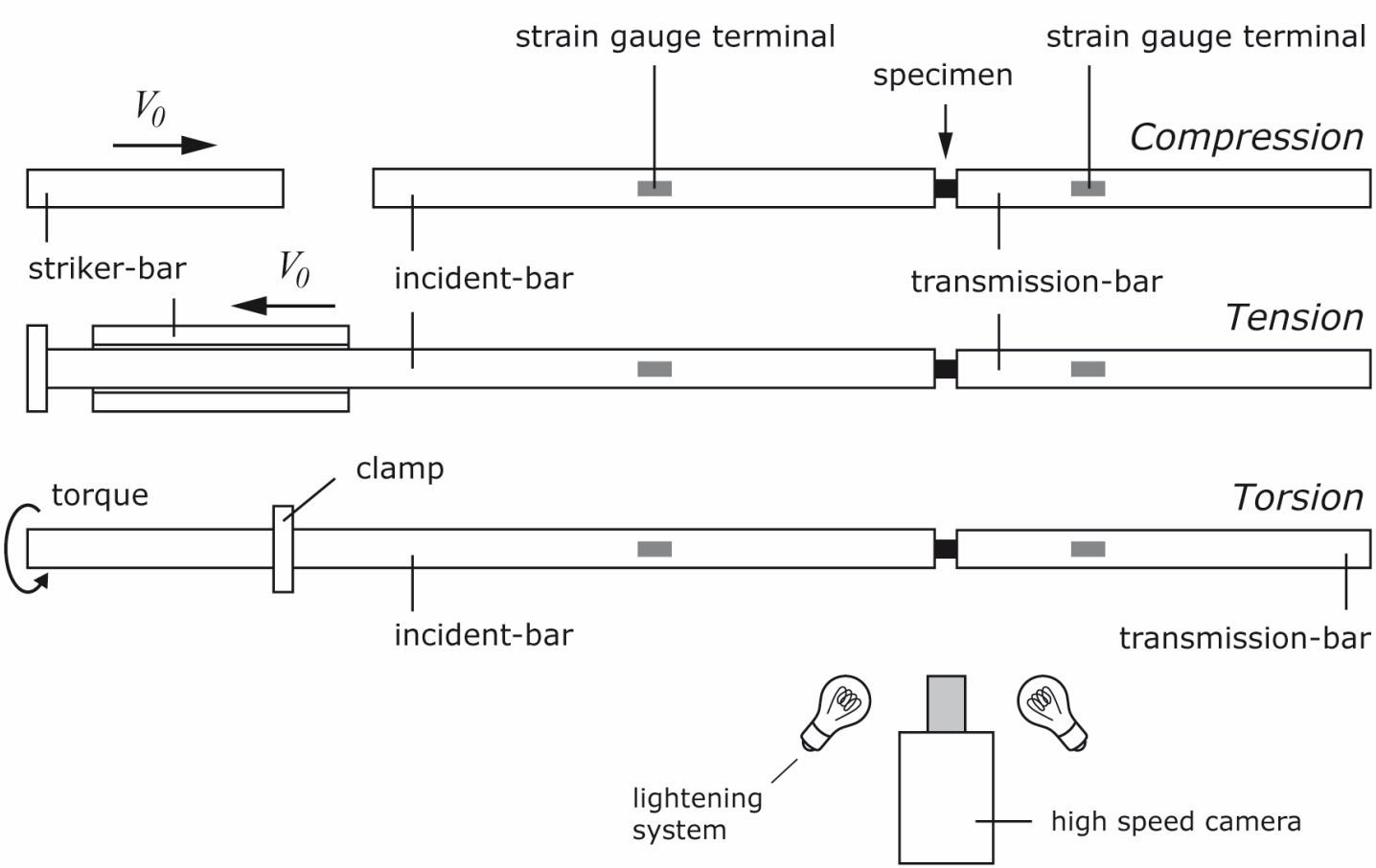


- Contactless measuring technique
  - max. strain limit higher than strain gauges
- Full 2d strain field $\{\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}\}^T$
  - ideal for orthotropic specimen behaviour
- Verification of uniform specimen deformation and strain distribution



- High speed photography reveals deformation and failure mechanisms

Compression-, Tension- and Torsion Setups



LCC Setups

- ∅ 16, 18, 25 mm steel bars &
- ∅ 16 mm aluminum bars

- ∅ 16, 20, 25 mm titanium bars

- ∅ 16 mm titanium bars &
- ∅ 16 mm aluminum bars

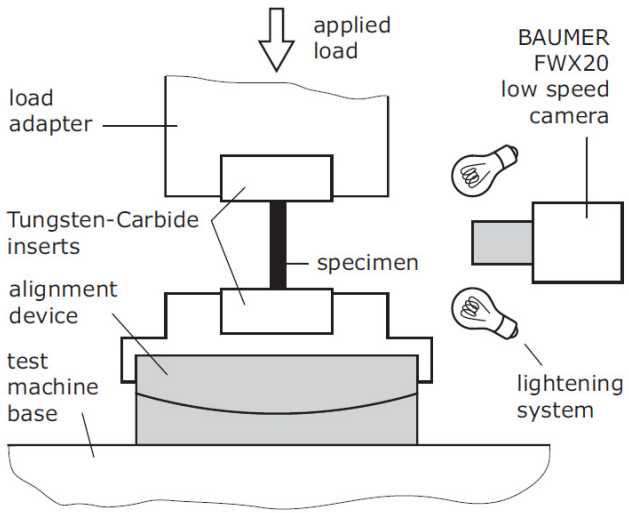
Photron SA5

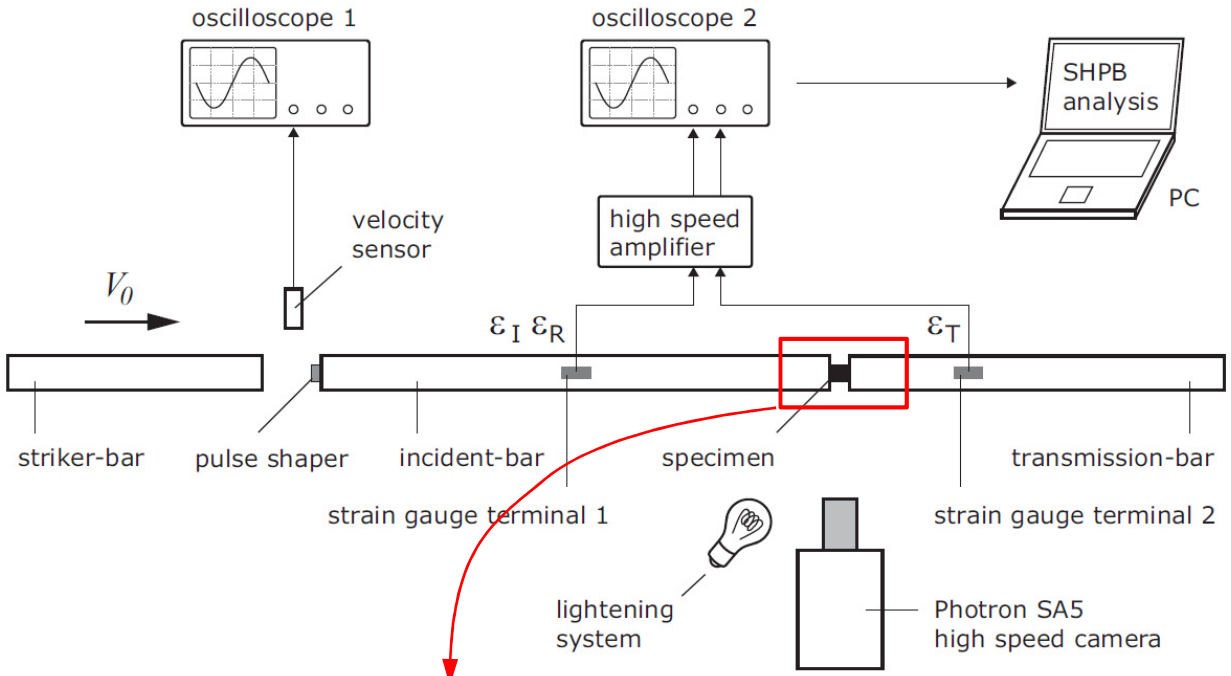
max. frame rate: 775000 fps
typical frame rate for SHPB tests: 100000 fps

Test Examples with Compression-Bar Setup

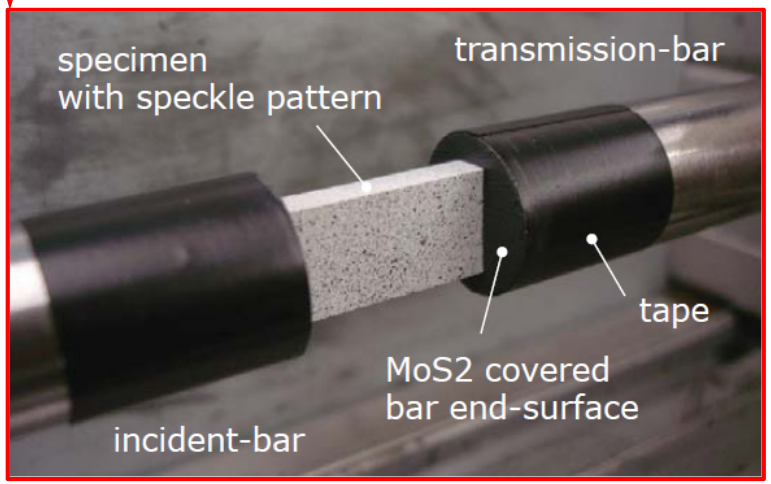
Hopkinson-Bar Setup for Dynamic Tests

Quasi-Static Reference Test Setup





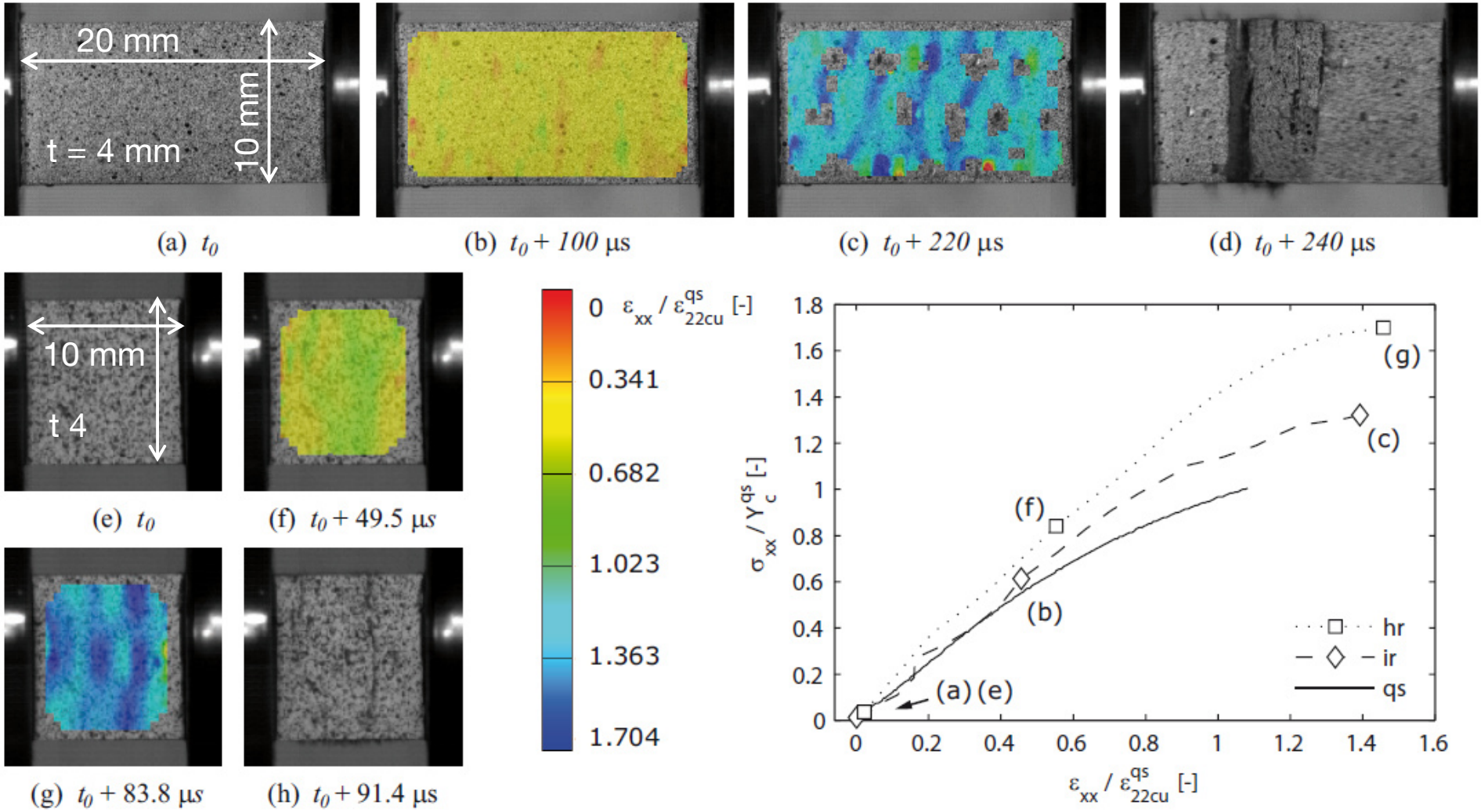
Specimen strain obtained with digital image correlation (DIC) using GOM ARAMIS system



Strain rates:

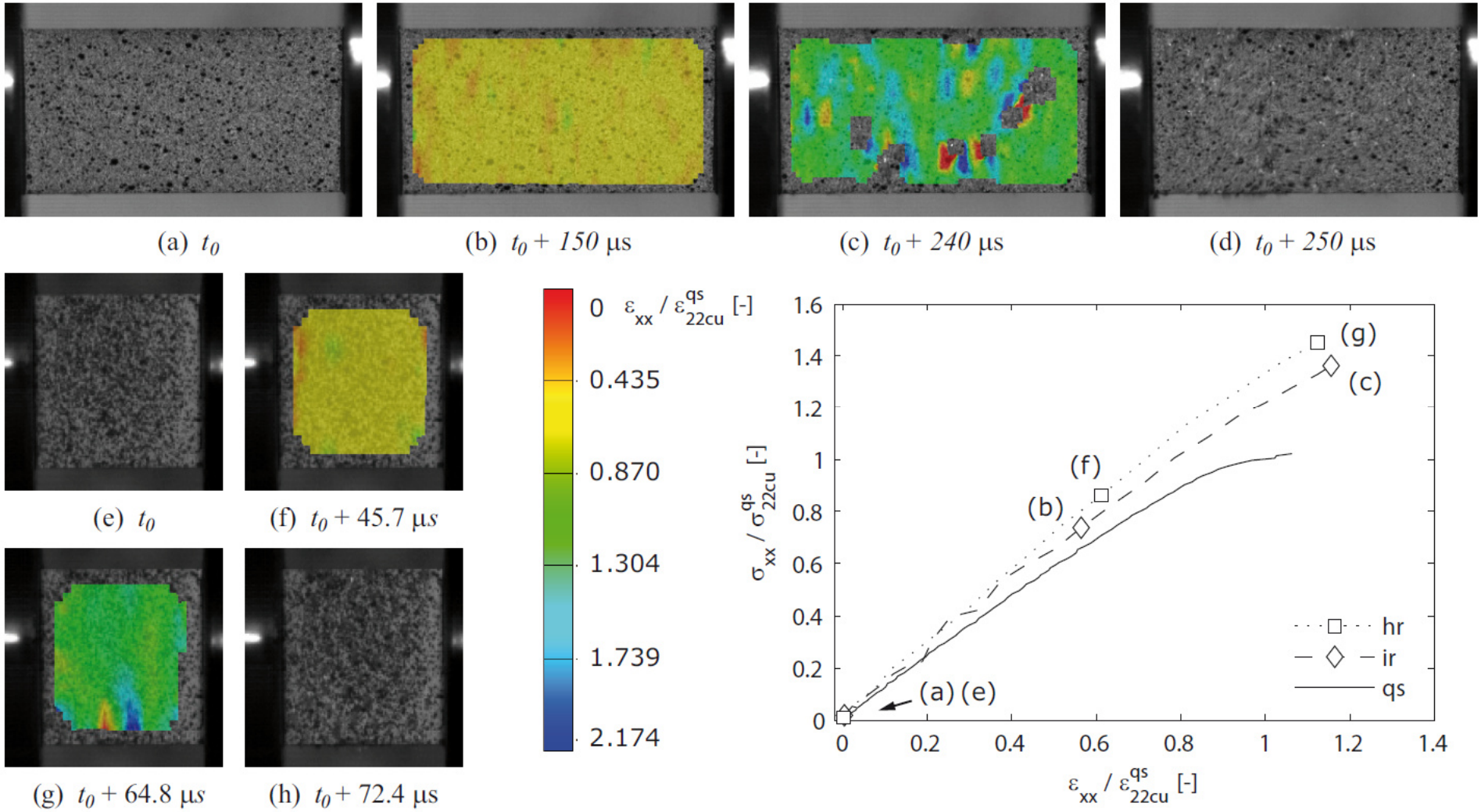
Quasi-static (QS):	0.0004 s^{-1}
Intermediate rate (IR):	≈ 200 s^{-1}
High rate (HR):	≈ 1000 s^{-1}

Axial strain fields for intermediate and high rate unidirectional fabric carbon-epoxy 90° compression test



[Koerber et al., submitted to International Journal of Solids and Structures, 2014]

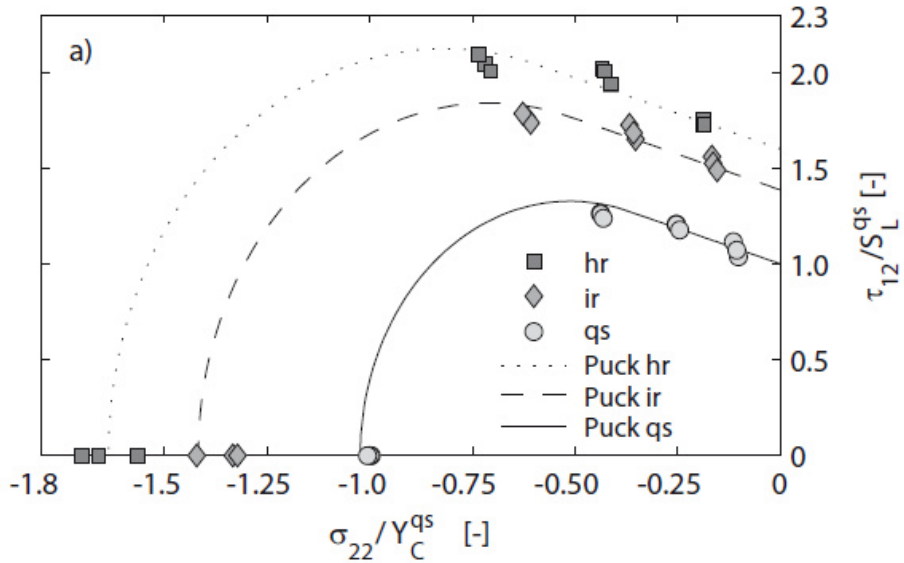
Axial strain fields for intermediate and high rate 8-harness-satin S2 glass-epoxy 90° compression test



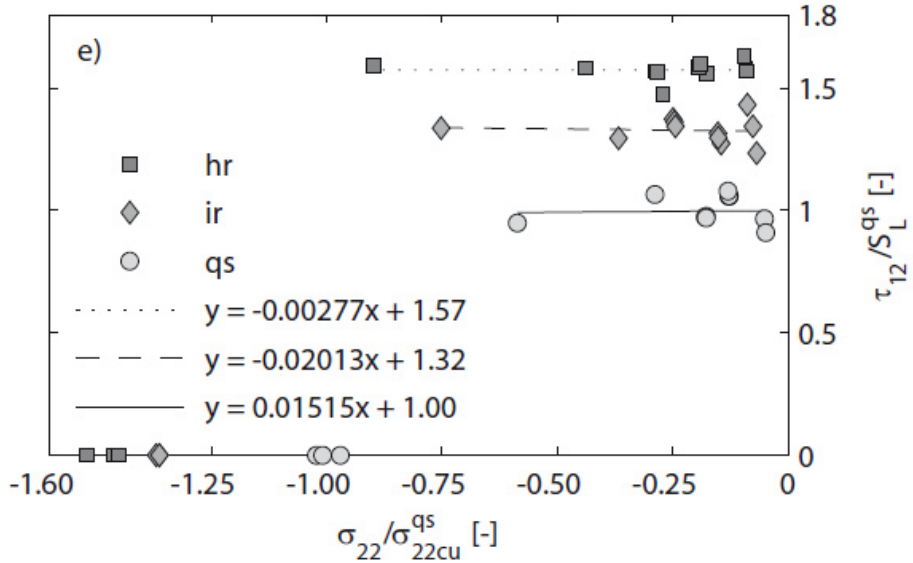
[Koerber et al., submitted to International Journal of Solids and Structures, 2014]

Strain Rate Effect on the $\sigma_{22} - \tau_{12}$ Failure Envelope

UD fabric carbon-epoxy



8-harness-satin S2 glass-epoxy



Strength component in material COS obtained from strength in loading COS via coordinate transformation:

$$\sigma_{22} = \sigma_{xx} \sin^2 \beta \quad , \quad \tau_{12} = -\sigma_{xx} \sin \beta \cos \beta \quad , \quad \beta = \theta_0 + d\theta$$

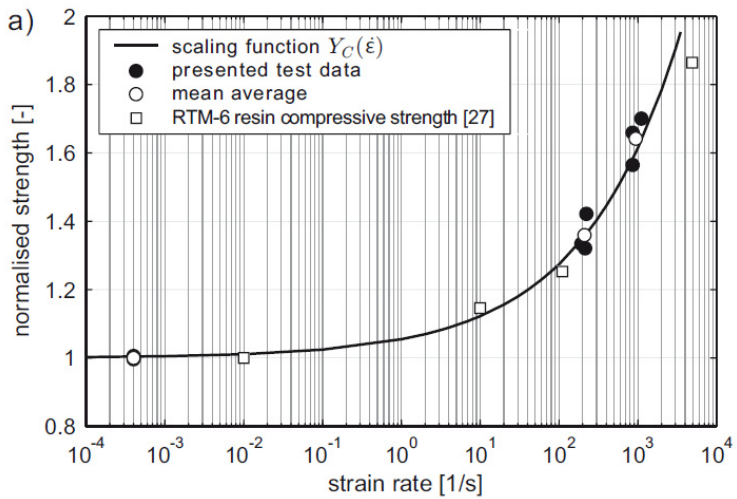
[Koerber et al., submitted to International Journal of Solids and Structures, 2014]

Strain Rate Trend Approximation via Cowper-Symonds Type Scaling Function

$$f(\dot{\varepsilon}) = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{p}}$$

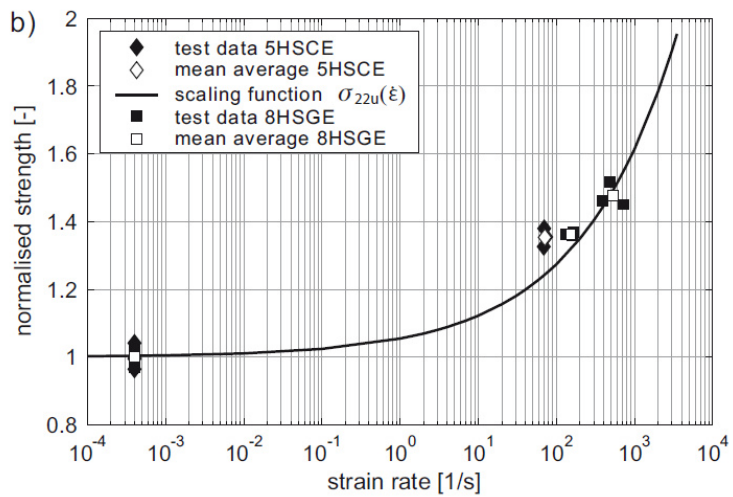
$$D = 4000$$
$$p = 2.85$$

UD fabric carbon-epoxy
transverse compressive strength



$$Y_C(\dot{\varepsilon}) = Y_{C,qs} \cdot f(\dot{\varepsilon})$$

5-harness-satin carbon-epoxy,
8-harness-satin S2 glass-epoxy
compressive strength (weft)

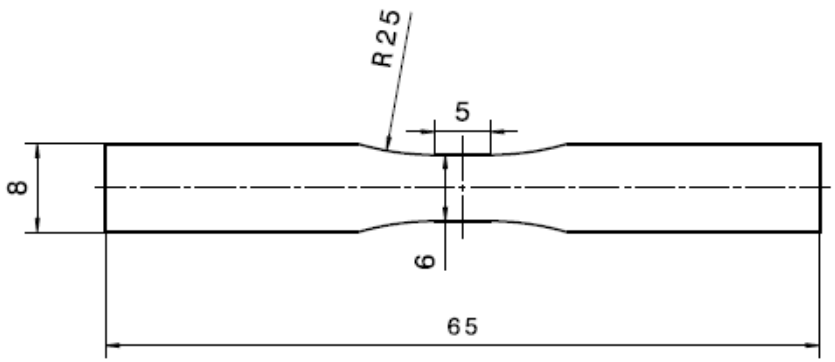


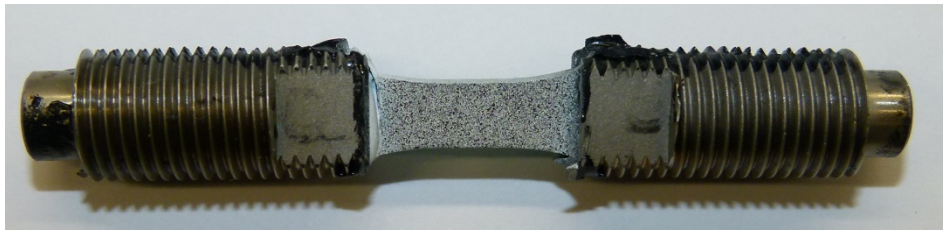
$$\sigma_{2cu}(\dot{\varepsilon}) = \sigma_{2cu,qs} \cdot f(\dot{\varepsilon})$$

[Koerber et al., submitted to International Journal of Solids and Structures, 2014]

Test Examples with Tension-Bar Setup

Specimen Geometry





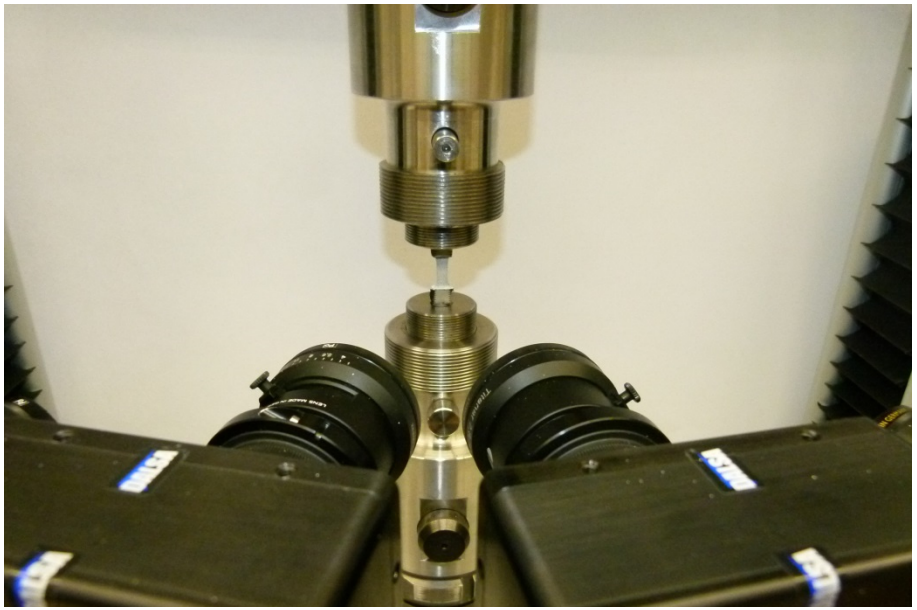
Specimens are bonded into slotted end caps

Same specimen geometry used for quasi-static reference tests and dynamic tests performed on the Hopkinson-bar to ensure comparability of results

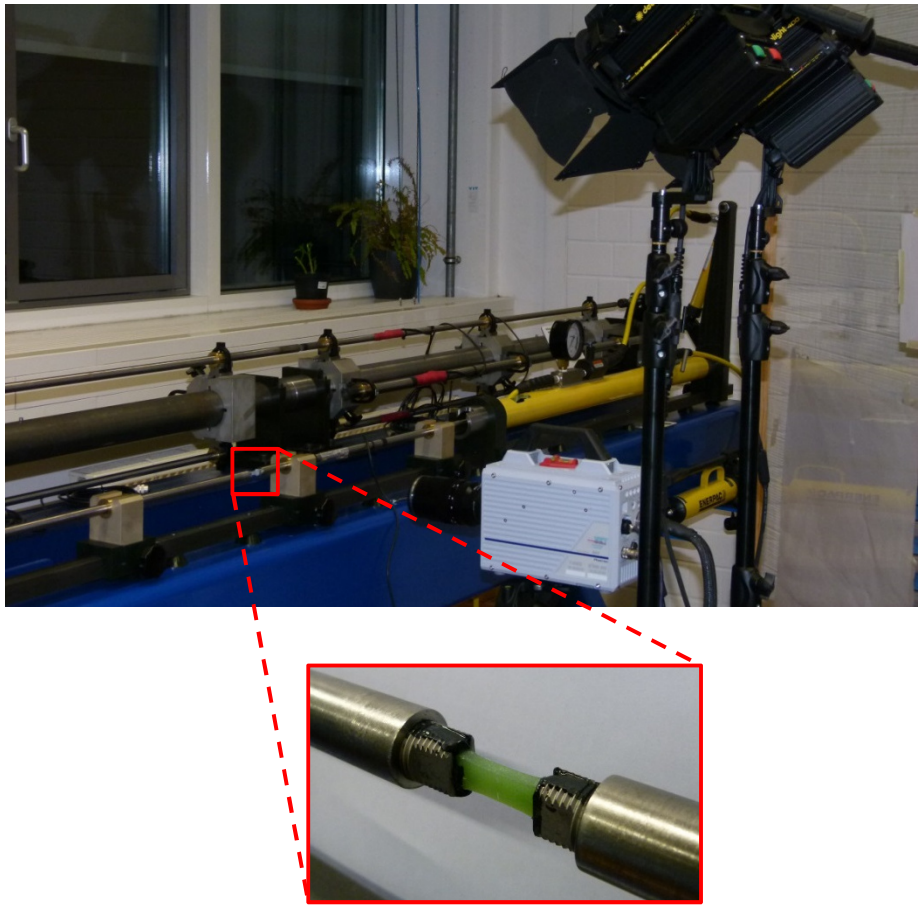
Shown specimen prepared for ∅ 16 mm titanium Hopkinson-bar setup

Test Setup

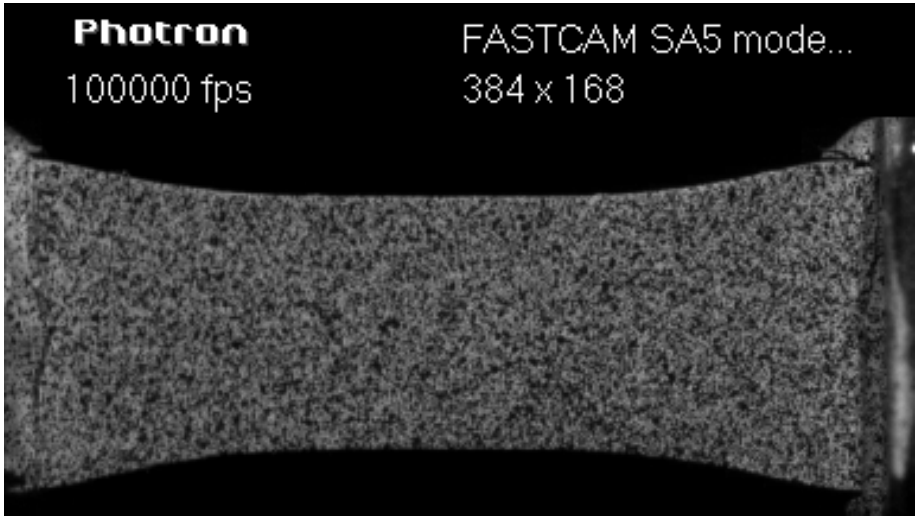
quasi-static reference test setup for
electro-mechanical test machine



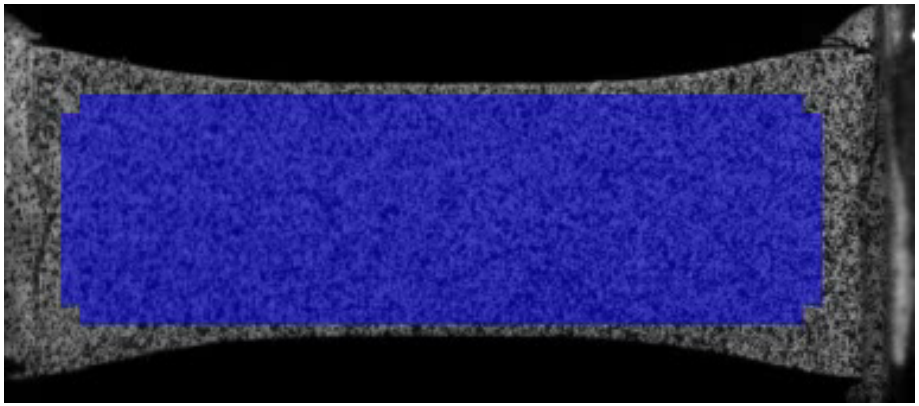
dynamic test setup for
∅ 16 mm titanium Hopkinson-bar



Dynamic Plain-Weave E-Glass-Epoxy Tensile Test

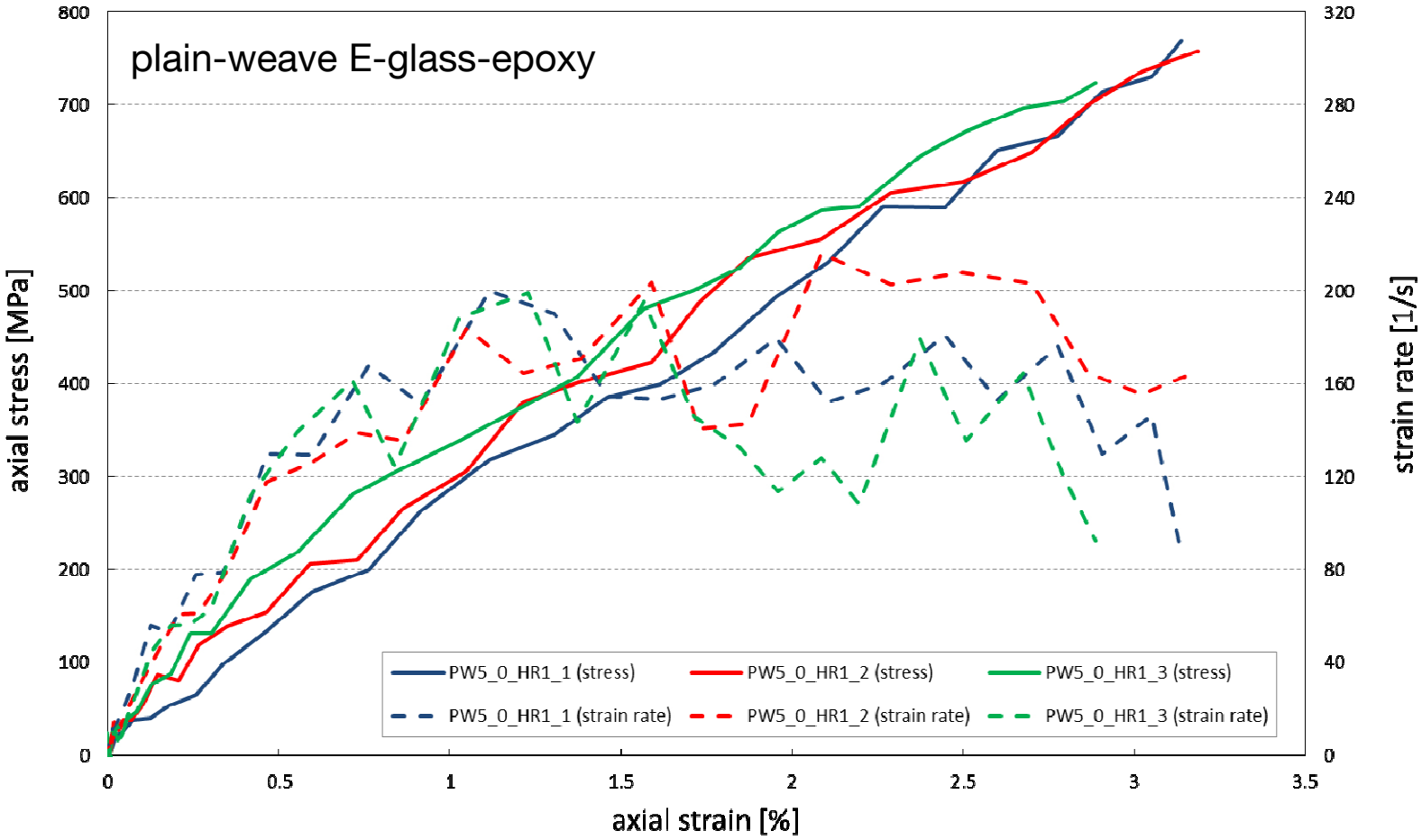


Video sequence captured with Photron SA5 high speed camera

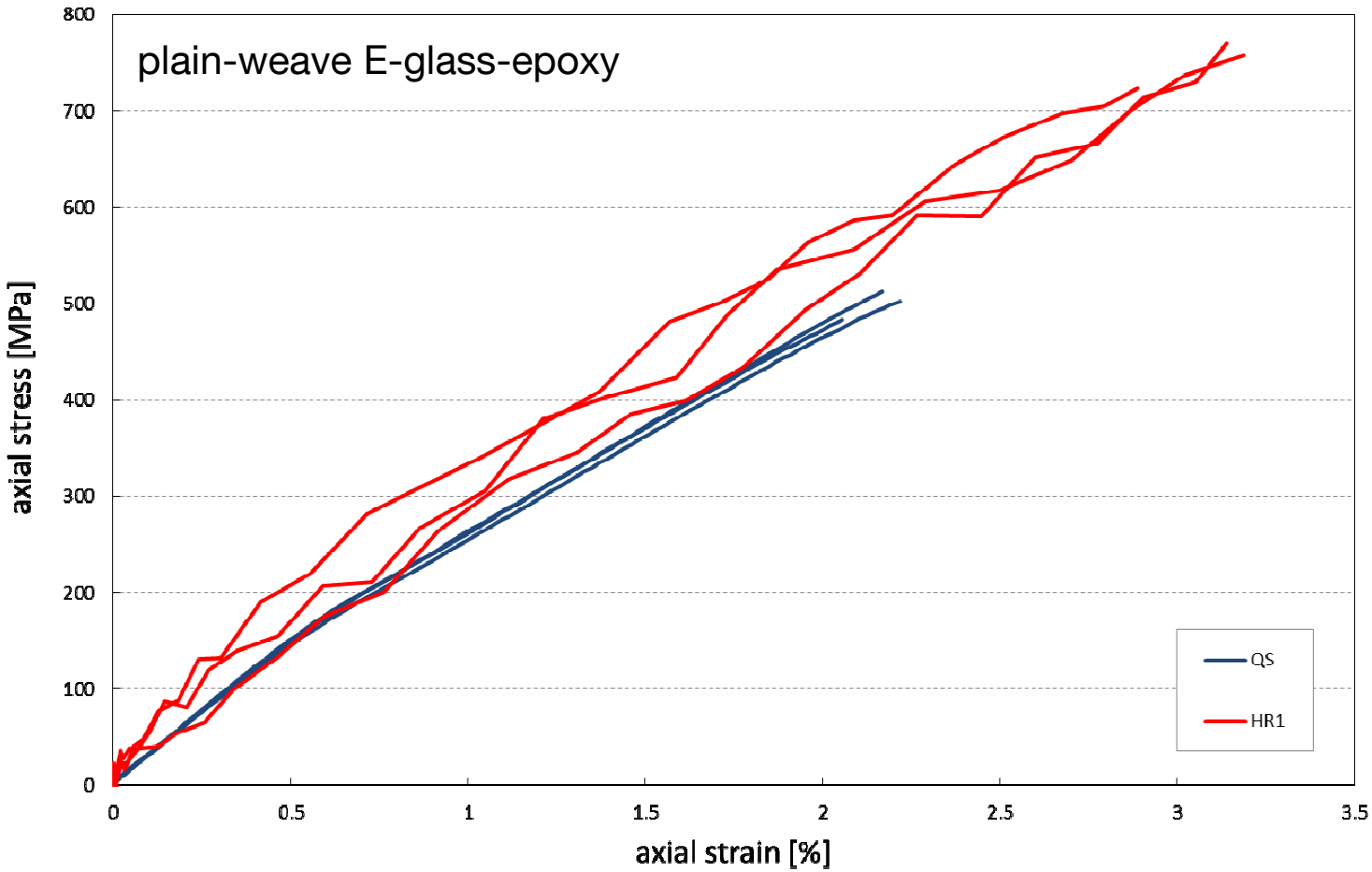


Axial strain-field determined with ARAMIS DIC system

Dynamic Stress-Strain Curve and Strain Rate



Comparison of Quasi-Static and Dynamic Material Behaviour



Conclusion

- The split-Hopkinson bar method is ideally suited for dynamic material characterisation of composites in the strain rate range of $10^2 - 10^3\ s^{-1}$

- Pulse shaping is required to obtain constant strain rates and an early dynamic equilibrium state
  - ramp shaped incident wave for linear stress-strain behaviour
  - Trapezoidal shaped incident wave for non-linear stress-strain behaviour

- Optical strain measurement techniques, such as digital image correlation, are ideally suited to obtain all strain components of orthotropic materials and are further useful to evaluate the uniformity of the specimen deformation

- High speed photography reveals specimen deformation and failure mechanisms

Vielen Dank für Ihre Aufmerksamkeit